Nanosecond pulse generation from a self-injected laser-pumped dye laser using a novel cavity-flipping technique

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The observation of regenerative oscillation in a laser-pumped dye laser is reported. Pulse trains of 1-nsec pulses have been observed from a rhodamine 6G dye laser pumped with a 50-nsec pulse at 5320 Å. The regenerative oscillation is produced by using a novel cavity-flipping technique recently developed. The principle of this technique and experimental results in a dye laser are described.

Previously, techniques commonly employed for generating short pulses from a dye laser, either flashlamp-pumped or laser-pumped, have been passive mode-locking using a saturable absorber or synchronized pumping with another mode-locked laser.[1] Short pulses in nanosecond and subnanosecond durations have also been observed in a N_2-laser-pumped dye laser using controllable resonator transient effects.[2,3]

In this Letter, a different technique of generating short optical pulses from a dye laser is described. This technique employs the principle of regenerative oscillation through amplification of a seeded pulse, which is self-generated inside a cavity. This seeded pulse is produced by a novel technique, termed cavity-flipping, to be described below. This technique was recently developed and successfully demonstrated in a Nd:glass laser and a Nd:YAG laser to produce short optical pulses over a range from nanoseconds to picoseconds.[4,5] Specifically, the application of this technique to a laser-pumped dye laser is reported in this Letter. Nanosecond pulse trains have been produced in a regenerative rhodamine 6G (Rh6G) dye-laser oscillator pumped with a frequency-doubled, Q-switched Nd:glass laser.

The purposes of this study are twofold: first, to describe experimental results obtained in a laser-pumped dye laser using the novel cavity-flipping technique, and second, to demonstrate the generic nature of this new technique for efficient generation of short optical pulses by applying it to a dye medium having a much higher gain than that of a Nd:glass or a Nd:YAG laser.

The experimental setup is shown in Fig. 1. The pump pulse generated from a frequency-doubled, Q-switched Nd:glass oscillator using a $LiIO_3$ crystal (10 mm × 10 mm × 10 mm) was of TEM_{00} mode, 50 nsec, and several millijoules at 0.53 μm and was polarized in the plane parallel to the paper. The pump beam was focused upon a dye cell through a 45° dichroic mirror (M3), which was transmissive to the pump beam and reflective to the dye-laser beam. The 8°-wedged, 10-mm-long dye cell contained Rh6G in methanol (1×10^{-4} mol). The cavity contained two polarizing elements, a Glan prism (P2) and a calcite prism (P1). The use of the calcite prism was to increase the polarization contrast ratio and to reduce the dye-laser linewidth to about 0.2 nm at 560 nm. The cavity reflectors consisted of a 2-m radius-of-curvature dielectric mirror (M2) (R = 100%), and a flat-output mirror (M1) (R = 50%). The physical length of the cavity was l_c = 75 cm with l_2 = 22 cm and l_1 = 53 cm, where l_1 and l_2 are defined in Fig. 4. The novelty of the cavity is the inclusion of a Pockels cell (PC2), which was made of deuterated KD*P and was driven with a krytron-switched Blumlein circuit[6] providing a half-wave high-voltage pulse with a duration of 7 nsec (FWHM) and a risetime of about 1.5 nsec.

In experiments, a fast photodiode was used to monitor the Q-switched pulse at 1.06 μm from the Nd:glass oscillator, and the output from the photodiode was used to trigger the Blumlein circuit. The Pockels cell was initially at a polarization state 1, defined as being fully transmissive to a beam in the polarization plane parallel to the paper. When a half-wave voltage pulse was applied to the Pockels cell, its polarization state was flipped from state 1 to state 0 for an interval of τ_g and

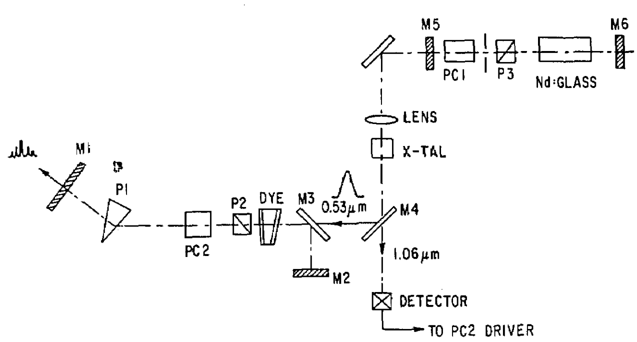

Fig. 1. Schematic of a regenerative dye-laser oscillator. The experimental setup: M1, 50% flat mirror; P1, Brewster-angle calcite birefringent prism; PC2, cavity-flipping Pockels cell; P2, Glan prism; DYE, flowing dye cell, 8° wedged, 10-mm gain length; M3, dichroic mirror; M2, 2-m, 100% dye-laser mirror; M4, 1.06- and 0.53-μm beam splitter; X-TAL, 10-mm $LiIO_3$ crystal, type I, phase matched at 1.06 μm; M5, 80% flat; PC1, Q-switching Pockels cell for Nd:glass oscillator; P3, dielectric polarizer; M6, 5-m, 100% mirror.

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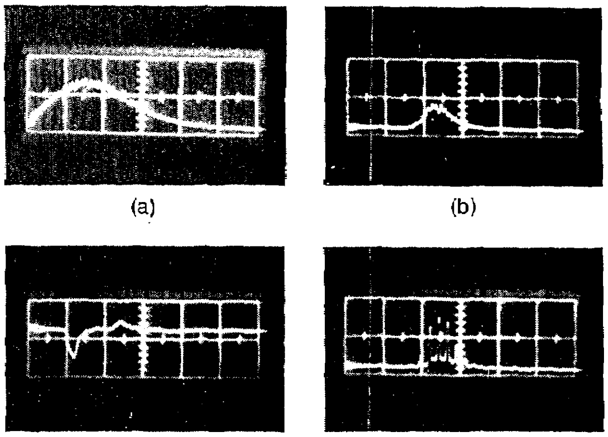

Fig. 2. Time sequence for (a) pumping pulse at 0.53 μm, (b) normal dye-laser pulse when PC2 was turned off, (c) the half-wave voltage pulse applied to PC2, and (c) the resulting regenerative oscillation from a cavity-flipped dye laser oscillator (time scale: 20 nsec/cm).

then back to state 1, where state 0 is defined as being fully transmissive to a beam in the polarization plane orthogonal to the paper. Figure 2 shows the time sequence of the pump pulse, the normal dye-laser pulse, the cavity-flipping voltage pulse, and the resulting regenerative dye-laser oscillation. Figure 2(a) shows the 50-nsec pump pulse at 0.53 μm. Figure 2(b) shows the corresponding dye laser pulse when the Pockels cell was turned off. This is a typical laser-pumped dye-laser pulse with its pulse width determined by the oscillation condition. Figure 2(c) indicates the half-wave voltage pulse applied to the Pockels cell, and Fig. 2(d) shows the resulting regenerative oscillation from the dye laser. In these figures, a Tektronix 519 CRT was used to display the waveforms and was externally triggered with the output from the fast photodiode employed simultaneously for triggering the Pockels cell. The signals in Figs. 2(a), 2(b), and 2(d) were measured with a fast vacuum photodiode (Korad KD-1) with 0.5-nsec resolution. The waveform shown in Fig. 2(c) is the high-voltage pulse monitored at the 50-Ω terminal of the Pockels cell. This figure shows the qualitative high-voltage-pulse waveform and switching time with respect to the dye-laser pulse [Fig. 2(b)] and the regenerative pulses [Fig. 2(d)], respectively. In Fig. 3, a detailed waveform corresponding to that shown in Fig. 2(d) is depicted to show the substructure of regenerative oscillation from the dye laser. The individual pulse width seen is about 1 nsec, with an interpulse period of about 5 nsec, which is equal to the cavity round-trip time τ_c.

The formation of regenerative oscillation can be explained by using Fig. 4 as follows: A longitudinal end-pumped dye laser, including a polarizing element (P) and a Pockels cell, is depicted schematically in Fig. 4(a). Assume that the polarization of both pump beam and dye laser is in the plane parallel to the paper. The cavity is divided into two portions, l_1 and l_2, by the Pockels cell located in close proximity to the polarizing element. The waveform illustrated on the left in Fig. 4(b) shows the dye-laser pulse operated under normal conditions. The solid line on the right in the figure depicts the intracavity spatial distribution $I(x,t)$ of the corresponding pulse along the longitudinal direction of the cavity axis. Normally, a typical dye laser pulse of, say, 20 nsec is about four times the cavity round-trip time τ_c. At any given instance, the intracavity circulating power distributes continuously along the cavity axis. However, the circulating power distribution is significantly modified as soon as a half-wave voltage is applied to the Pockels cell for an interval of τ_g (say, $\tau_g > \tau_c$). Consequently, the transmitting state of the cavity is said to flip from the original state 1 to state 0, defined previously. As a result, the intracavity circulating power distribution is modulated, and it is shown in Fig. 4(c) after a round-trip time from $t = 0$. That is, the signal ($t = 0^-$) initially circulating inside the cavity portion l_1 is dumped out of the cavity via the polarizing element, while the signal ($t = 0^-$) initially inside the cavity portion l_2 remains calculating inside the cavity as it travels twice through the Pockels cell during a round-trip period τ_c after cavity-flipping. The remaining portion of the signal produced at the maximum inversion with a pulse length equal to l_2 can be considered a seeded pulse, becoming regenerative until the gain of the laser is saturated. From the moment at which the cavity-flipping takes place, one could view the cavity as being injected with its own seeded pulse. The length of this seeded pulse is shown as the solid line in Fig. 4(c) for $\tau_g = \tau_c$ or $\tau_g \gg \tau_c$. It can be shown that the length of the seeded pulse produced by cavity-flipping depends on the relative values of τ_g, τ_c, l_1, and l_2.[4,5] The minimum pulse width obtainable with this technique is limited by the risetime and the transit time of the Pockels cell. Shorter pulse is achievable by using a nonlinear absorber for pulse compression.[4,5]

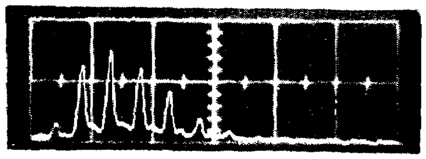

Fig. 3. A typical regenerative oscillation waveform (time scale: 10 nsec/cm).

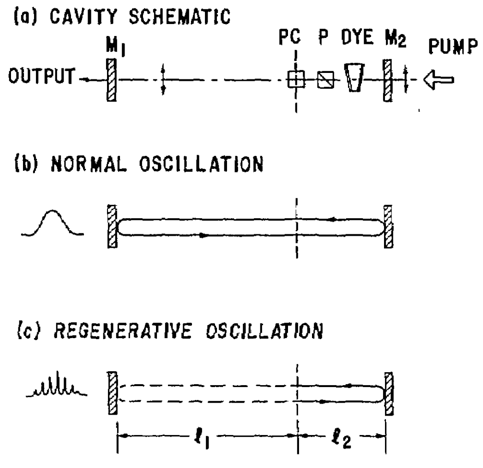

Fig. 4. Schematic illustration of the formation of regenerative oscillation in a cavity-flipped dye-laser oscillator.

It is interesting to note that the cavity-flipping *immediately precedes* the normal dye-laser pulse, while the regenerative oscillation persists until the gain is saturated. This suggests the possibility of applying this technique to a long-pulse dye laser such as a flash-lamp-pumped dye laser. The timing for cavity-flipping is rather critical. If the Pockels cell was activated earlier than the proper time, the regenerative oscillation was not observed. If later, only part of the pulse showed regenerative oscillation. Pulse trains with an interpulse period equal to $\tau_c/2$ were frequently observed when the cavity parameters, such as the half-wave voltage, were not adjusted properly. Typical pulse energy measured from the dye laser for both Figs. 2(b) and 2(d) was about 30 μJ.

In summary, I have described a new technique, termed cavity-flipping, for generating short pulses from a dye laser. Nanosecond pulse trains have been produced by using this technique in a regenerative laser-pumped Rh6G dye laser. This technique has been recently applied to Nd:glass and Nd:YAG lasers. Short pulses of nanoseconds to picoseconds have been generated in these media. These results will be discussed in future publications. It is significant to note that the solid-state laser and the dye laser are two types of lasers of widely different characteristics. The applications to both types of lasers to date have demonstrated the generic nature of the new technique for short-pulse generation. It suggests the possibility of applying this technique to other types of lasers, such as CO_2 lasers, excimer lasers, and chemical lasers, to name a few. The operation of this technique is as easy as operating a Pockels-cell Q-switched oscillator and has approximately the same efficiency as that expected from a normal oscillator. Furthermore, the pulse-train buildup with respect to cavity-flipping time $t = 0$ is well defined. Consequently, the pulses are synchronizable. The technique is expected to find applications to other types of lasers for efficient short-pulse generation.

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